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Tel: +381 18 23 953 Fax: +381 18 24 488

INVESTIGATIONS OF THE ELECTRICAL DISCHARGE FORMATION MECHANISMS IN NITROGEN AND KRYPTON

Bošan Dj. A.[1]
Radović M. K.[2]
Zlatić V. Ž.[3]
Jovanović T. V.[1]

[1]Faculty of Electronic Engineering, PF 73, 18001 Niš, Yugoslavi
[2]Faculty of Philosophy, Department of Physics, PF 92, 18001 Niš, Yugoslavia
[3]Faculty of Civil Engineering, PF 115, 18001 Niš, Yugoslavia

Abstract: Different forms of the discharge formation mechanism and the corresponding formative times (t_f) of electrical discharge in nitrogen and krypton-filled, cold electrode, diodes were investigated. Using the 1 mbar pressure and overvoltage of approximately 1 % above the static breakdown value (U_s), total formative times up to 10^3 s were obtained. In this particular case, the relaxation time of the diode, after previous glow (afterglow time τ), had to be longer than 48 hours.

Having in mind this fact, one can conclude on the importance of the step by step ionization and on the importance of the presence of neutral metastable molecules of nitrogen or krypton atoms in the process of discharge formation under given conditions.

1. Introduction

The formative time of the electrical discharge in gases (t_f) and the phenomena linked to these processes have often been investigated over the last 100 years, after the fundamental papers of Paschen [1], Townsend [2 – 4] and the first statistical approach to the analysis of the scattering of measurement results of the statistical breakdown time delay (t_s) by Max von Laue [5]. Two quantities were mentioned that add up to the total time delay of electrical breakdown, i.e. $t_d = t_s + t_f$.

Most publications on discharge formation were dealing with cases of discharge conditions when t_f values were in the range of *ns* or *μs*, very rarely higher. This was mainly due to the fact that the experiments were performed, in most cases, in laboratories of large electrical engineering companies with the aim to check and/or improve power supply systems and switchgears. The gases were air or other insulating gases, the pressure was atmospheric one or higher, the voltage was of order of *kV* and the electrode gap was 1 cm or wider.

In the 1940s fundamental results on these investigations had already been published. Such was dominant practice, although the long formation times were theoretically elaborated and the corresponding test equipment was constructed and

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used. The following monographs contain details of these investigations, as well as further bibliographic data [6-9] and the proceedings of the conferences: Int. Conf. on Phenomena in Ionized gases, Int. Conf. on Gas Discharges and their Appl., (GB), Int. Symp. on Gaseous Dielectrics (USA) etc.

The present investigations are rather different. They are the continuation of the investigations, presented in the papers [10-12] on long formative times etc. In these experiments, rare and permanent gases under the pressure mostly between 0.1 and 100 mbar were used and the voltage was usually 1% up to 20% above the static breakdown voltage. Trial runs done under these conditions demonstrated the presence of t_s times, up to the order of 10^3 s and t_f times of order 10^2 and 10^3 s.

2. Experiments and results

The basic setup for discharge formation investigations is shown in Fig. 1. A preset DC voltage (U_w) from the stabilized power supply (DC1, stable within 0.1%) was applied to the diode. Data were recorded via an osciloscope with computer memory. In all described experiments, the currents were initiated by a minimal necessary electron bursts, with space charge of about 1 nA·s, at time $t = 0$. Using the switch $P2$, an additional voltage (usualy between 500 and 1000 V) from the power supply DC2 can be superimposed to the voltage U_w and applied to the diode before the t_f measurements. Through the resistance $R3$ (2.5 GΩ), a small current is flowing through the diode for a preset short time enough to establish the necessary initial electron burst and to reduce the statistical time delay to be resonably short in the mean measuring process. This preconditioning process influenced only the concentration of ions and excited states in the gas-filling of the diode.

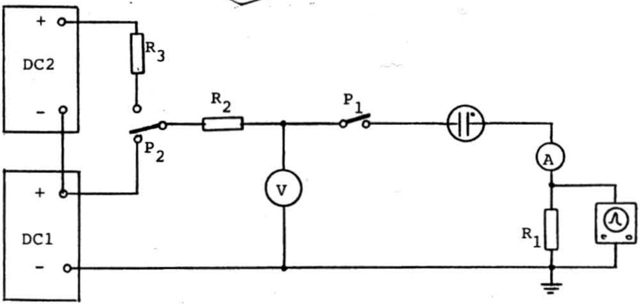


Fig.1. Measuring circuit.

2.1 Nitrogen filled diode at 1.3 mbar

These experiments were performed with a 90 cm^3 glass diode containing two spherical, 10 mm diameter, pure iron electrodes with a 3 mm gap. The impurity of the nitrogen filling at 1.3 mbar was less than 10 ppm. For these measurements, each new diode was preconditioned before the first t_f measurement by electrical pulses in order to stabilize the characteristics [13]. The static breakdown voltage (U_s) was 364 V DC and the applied overvoltage [$100 \cdot (U_w - U_s)/U_s$] ranges between 1.6% and 3% .

At the application of such low overvoltages, three different types of discharge formation mechanisms could be observed in nitrogen, that might be related to the diode characteristic and the circuit conditions, for which the saturation current reached aproximately the following ranges:

I. $i_S < 0.2\ \mu A$,
II. $0.5 < i_S < 10\ \mu A$ and
III. $10\ \mu A < i_S$

In all cases discharges were self-sustaining and were done in the regime of subnormal glow discharge ($\Delta U/\Delta i < 0$).

Discharge formation regime I

The dependence of the effective current values (i_{eff}) on time (t) due to this situation is shown in Fig.2, under the following conditions: $U_S = 364$ V, $U_w = 370$ V (1.6% overvoltage), $R_1 + R_2 = 34$ MΩ (Fig.1).

One can see on the osciloscope that the current consists of well-separated stochastically distributed pulses. In time intervals between succesive pulses the current values drop to zero. Typical shapes of these pulses are presented in Figs. 3a and 3b. The increase of the current i_{eff} can consequently be ascribed to the increase of the mentioned pulse rate in time. Strictly speaking, each pulse has its own formative time, however, in 40 minutes consider, the discharge is in its process of formation, and until i_{eff} reaches the i_S value the each new pulse is generated under conditions modified by the previous one [14]. After each pulse, a higher concentration of particles able to initiate the

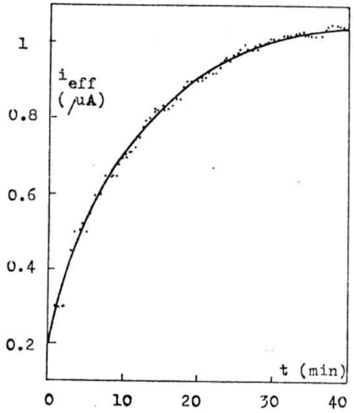
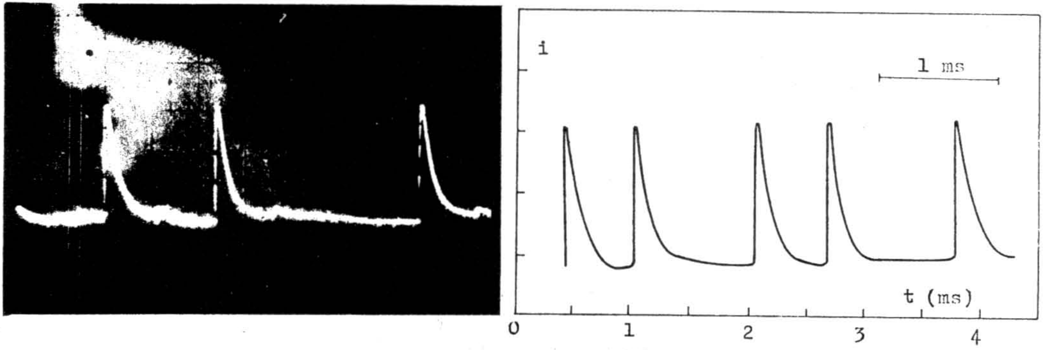


Fig.2. Formative time in the nitrogen filled diode under the discharge regime-conditions I.

breakdown remains in the gas, increasing the probability of new pulses appearance.



a b

Fig.3. Pulses with regime I. Fig. b is taken a few seconds after Fig. a.

However, due to the smallness of the applied overvoltage and the high resistance of the circuit, such a form of discharge mechanism is sustained as long as the voltage U_w is applied. Under these conditions there is no possibility that the discharge obtains DC component (i.e. that the current values between pulses be different from zero).

Discharge of this type usually occurs after long relaxation periods of the diodes (relaxation time is the interval between the cessation of the previous discharge and the next application of the voltage U_w on the diode). It is followed by the also long statistical time delays t_S, that can be of the order of 60 min. At low overvoltages and high circuit resistances such a discharge form may be maintained even at the current of the order of 1 μA.

Discharge formation regime II

When the cirrcuit conditions are modified, using the smaller resistance values of $R_1 = 4$ MΩ and $R_2 =$ 1.5 MΩ, the discharges formation form is changing qualitatively. A typical discharge formation is shown in Fig. 4, proceeding in two stages denoted by t_{f1} and t_{f2}. The voltage U_w is applied at the instant A. After the statistical time delay t_S, the discharge formation begins at B and the effective current value (i_{eff} , represented by a full line) reaches its saturation i_S at D (note the log time scale).The shaded part in Fig. 4 contains the current oscillations during the discharge formation time t_f, BCE being the lower and FGH the uper envelope of these oscillations. During t_{f1}, between B and C, pulses occur unperiodically, mostly with zero current values between them. The shape of the pulses in the t_{f1} time interval is the same as that in Figs. 3 a and 3 b. It can be seen that pulses occur unperiodically and that their probability of appearence rises with time. It can be seen (Fig.4) that the discharge formation proceeds during this interval, also lasting about 10 s.

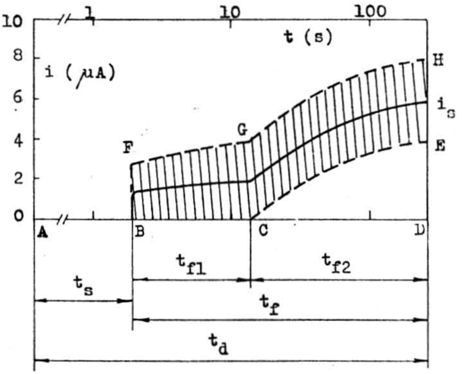


Fig.4. Discharge mechanism regime II in nitrogen.

Between C nad D (t_{f2} in Fig.4), pulses appear periodically and form the periodical current oscillations superimposed on the direct current component presented by CE. Frequencies of these oscillations depend on the characteristics of the diode as well as on that of the circuit itself [15]. A typical part of these oscillations is shown in Fig.5 again for a 4.5 ms interval. Under these conditions, the effective value of the current rises with time and reaches its saturation value i_s at D, that depends on the voltage U_w and the circuit impedance.

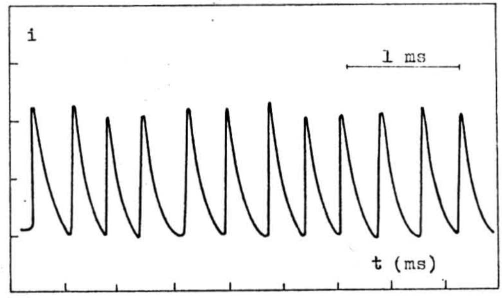


Fig.5. Periodical pulses type.

Occasionally, under identical conditions, the formative time t_{f1} splits into two parts as in Fig.6, where t_{f1a} and t_{f1b} are well-separated by the interval without pulses at all.

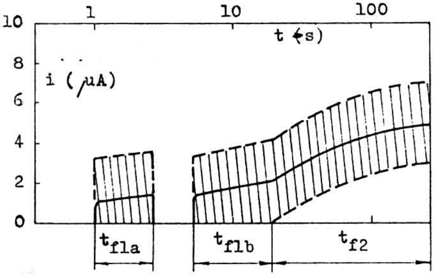


Fig.6. Spliting of the formative proces.

On the other hand, "regular" time intervals t_f, t_{f1} and t_{f2} strongly depend on the circuit conditions which can be described trough saturation current value. The measured dependencies, up to i_S values of 10 μA are presented in Fig.7.

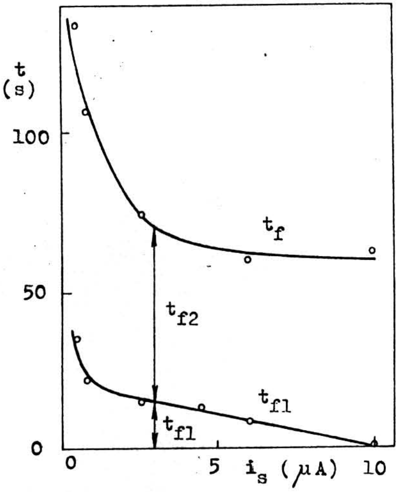


Fig.7. Dependence of the t_f, on the diode and circuit conditions described through i_S.

The formative time t_f splits into two parts under conditions when the relaxation time of the diode is longer than 24 hours (48 is enough), the gas pressure does not exceed 2 mbar, there is no external ionization present and without applying the initial electron burst.

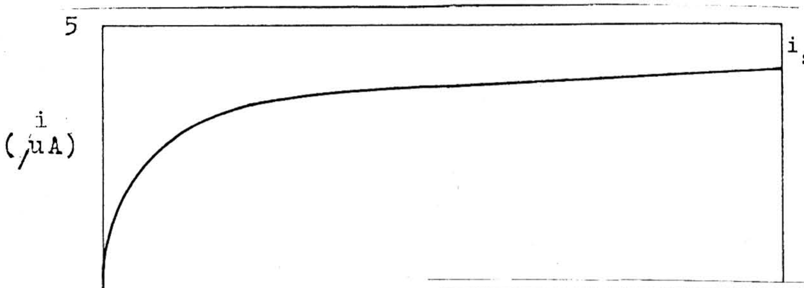
Discharge formation regime III

At saturation current $i_S > 10\ \mu A$, the discharge formation develops only by means of the mechanism described under phase t_{f2}, regardless of the values of U_w, R_1 and R_2 at which the current i_S is obtained.

2.2 Nitrogen filled diode under pressure of 6.7 mbar

This diode differed from the previously described one by the volume (380 cm^3), the gap (1 mm) and the pressure. It showed the static breakdown voltage value of 320 V. All the measurements on this diode were also done in subnormal glow discharge region. The formative time was measured at an overvoltage of 22% and with $R_1 = 4\ M\Omega$ and $R_2 = 20\ M\Omega$ as in the circuit in Fig.1. The curve in Fig.8 shows the result. The current reaches its 60% saturation value in less than 1 ms and it still takes about 100 s to reach the saturation. The time expansion of the first part is shown in Fig.9 where the full t-scale value is 4.5 ms. The ringing of the curve is due to the external circuitry.

Fig.8. Formation of i_s under 22% overvoltage.



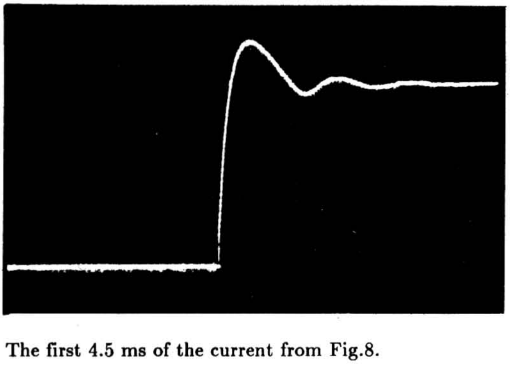


Fig.9. The first 4.5 ms of the current from Fig.8.

The strong dependence of t_f on the previous relaxation time of the diode is shown in Fig.10. Varying the circuit and other conditions, the discharge formation leads to different saturation values. The obtained dependence of the t_f on i_S is shown in Fig.11.

2.3 Krypton filled diode under pressure of 2.7 mbar

This diode is like the described one, filled with krypton under pressure of 2.7 mbar and with the electrode gap of 2 mm. The preconditioning was the same as in the diode mentioned as well as the measuring procedure. The discharge is also in selfsustaining glow regime.

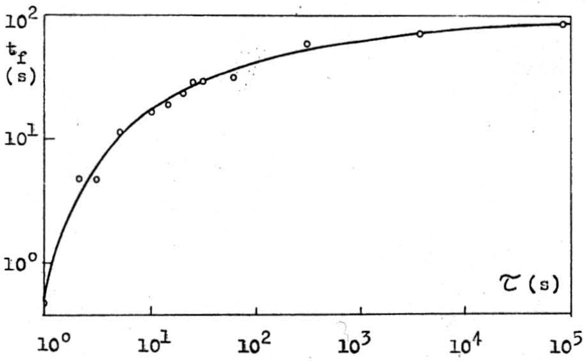


Fig.10. The t_f dependence on the diode relaxation (afterglow) time.

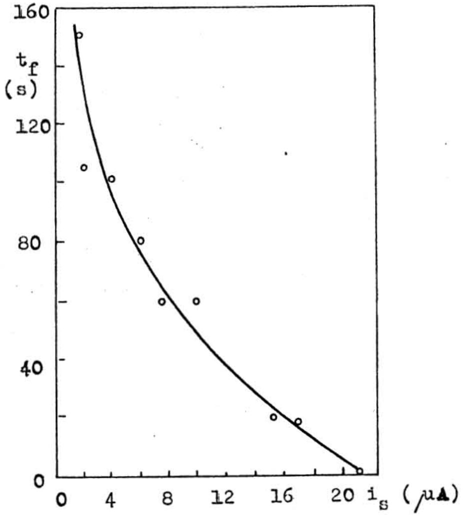


Fig.11. t_f dependence on the electrical condition (described through i_s).

The measuring conditions were the following. $U_S = 370$ V, $U_w = 380$ V (2.7% overvoltage), $R_1 = 4$ MΩ and $R_2 = 30$ MΩ. The result of this measurement is shown in Fig.12 where the full t-scale value is 100 ms. By the current i_{eff} of 2 μA it can be seen that the current consists of unperiodical pulses. Between some successive pulses, constant DC current component appears superimposed with periodical pulses with lower amplitudes. This kind of discharge does not change during the arbitrary long time.

Fig.12. Pulses in 2 μA discharge in krypton (full-scale 100 ms).

3. Discussion

The results obtained and especially the phenomenon represented in Figs.7 and 10, suggests the important role of two step ionization of the gas molecules or atoms in the discharge formation process in nitrogen at low values of applied overvoltages. As it can be seen, if all other conditions are kept identical, the discharge formative time t_f depends on the diode relaxation time τ.

As it was shown in many papers e.g. [16, 17], the state and the propereties of the gas at various τ values (for $\tau > 1$ s) differ mostly in the concentration of the long living metastable states of gas molecules that decrease in time. That decrease, as was shown in this case, lasts more than 24 hours [17, 18]. The increase of t_f with the decrease of the concentration of metastable states shows that in order to keep i_S constant, it is necessary to have a saturation of metastable concentration in the gas. Thus, for establishing the metastables saturation concentration mentioned, applying a definite U_w value and under constant conditions, a certain time, which increases with the afterglow period τ, is necessary.

According to literature [19-21], this metastable state in nitrogen is $N_2(\mathrm{A}^3\Sigma_u^+)$.

If this explanation of the phenomena obtained is acceptable, then the slow increase of the current, presented in Figs. 2, 4, 6 and 8, can be explained by the slow increase of metastable concentration up to the saturation concentration under the given conditions.

The decrease of the t_f (Figs. 7 and 11) with the increase of saturation current is then the cosequence of the increase of metastable generation rate due to the increase of the current flow through the diode.

In all mentioned cases, the saturation value of the current is established when equillibrium is reached between the generation and the deexcitation rates of long-living excited particles of the gas filling of the diode. In other words, during the entire discharge formation period t_f , the concentration of metastables in entire diodes tube volume, increases up to the saturation concentration distribution, which is reached at the same time as the current reaches its saturation.

The final conclusion is that the role of neutral metastables in breakdown formation and discharges processes increases with the decrease of the pressure and the applied overvoltage, i. e. that the t_f value depends significantly on the measuring and circuit conditions.

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ISTRAŽIVANJA MEHANIZAMA FORMIRANJA ELEKTRIČNOG PRAŽNJENJA U AZOTU I KRIPTONU

Bošan Dj. A.[1], Radović M. K.[2], Zlatić V. Ž.[3] and Jovanović T. V.[1]

[1]Elektronski fakultet, PF 73, 18001 Niš, Jugoslavija
[2]Filozofski fakultet, Studijska grupa za fiziku, PF 92, 18001 Niš, Jugoslavija
[3]Gradjevinski fakultet, PF 115, 18001 Niš, Jugoslavija

Sadržaj: U radu su prezentovani rezultati istraživanja različitih varijanti mehanizama formiranja električnog pražnjenja u azotu i kriptonu, kao i odgovarajućeg vremena formiranja (t_f). Istraživanja su vršena sa hladnim elektrodama, pod pritiskom od 1 mbar i sa prenaponima reda 1 %. Rezultati pokazuju da u ekstremnim uslovima, sa vremenom relaksacije diode od oko 48 časova, totalno vreme formiranja pražnjenja može dostići vrednost od 10^3 s.

Dobijeni rezultati sugerišu važnost stepenaste jonizacije i uloge neutralnih, metastabilnih čestica prilikom formiranja električnog pražnjenja pri navedenim uslovima.